# Axisymmetric vortex breakdown in constricted pipes

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## AXISYMMETRIC VORTEX BREAKDOWN IN CONSTRICTED PIPES

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We investigate numerically and theoretically the axisymmetric vortex breakdown occurring in a contracting pipe of finite extension, i.e. the transition from a smooth columnar state to a breakdown state exhibiting a recirculation bubble. Velocity distributions are prescribed at the pipe inlet under the form of Batchelor vortices with uniform axial velocity and variable levels of confinement. A numerical continuation technique is developed to follow the branches of nonlinear steady solutions when varying the swirl parameter. In the most general case, for Re=500, vortex breakdown occurs abruptly owing to a subcritical, global instability of the non-parallel, viscous columnar solution, and results in the coexistence of multiple stable solutions over a finite range of swirl. For highly confined vortices, a second scenario prevails, where the flow transitions smoothly from the columnar to the breakdown state without any instability. These results are reminiscent of those obtained by [2] and [1] where slip is allowed at the wall.

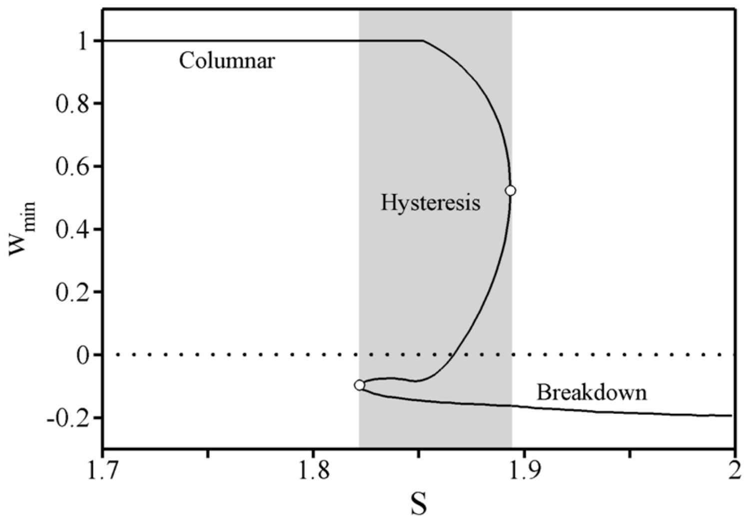


Figure 1: Bifurcation diagram illustrating the onset of vortex breakdown as the swirl is increased. The minimum axial velocity $u_{min}$ is plotted as a function of the swirl - $Re = 500$.

The effect of a low flow rate jet positioned at the pipe wall is then characterized in the perspective of control. Its effectiveness is evaluated in light of three practically meaningful criteria, namely the ability of the control to optimize either the stability domain or the topology of the columnar state, and its ability to alleviate hysteresis. For each criterion, an optimal jet position is determined from nonlinear simulations.

The results are in good agreement with those issuing from an weakly nonlinear asymptotic expansion of the Navier- Stokes equations, which yields two normal forms describing the two saddle-node bifurcations underlying the fold structure of the bifurcation. The open-loop control enters as a forcing term in the resulting amplitude equations.

# References

[1] P. S. Beran and F. E. Culick, The role of non-uniqueness in the development of vortex breakdown in tubes,*J. Fluid Mech.* **242**, 491–527 (1992).

[2] J.M. Lopez, "On the bifurcation structure of axisymmetric vortex breakdown in a constricted pipe"*Phys. Fluids* **6**, 3683–3693 (1993).